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Internal extinction of disc galaxies – I. High-resolution extinction map of NGC 6946

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ABSTRACT

Traditionally, it has been believed that extinction effects due to dust within the interstellar medium of external galaxies are rather small and can largely be ignored. Over the last 10 years, however, considerable doubt has been cast over the evidence to support this comfortable idea, and it has become clear that a more detailed analysis is required. Here, a new technique for mapping the extinction in disc galaxies with high resolution is presented.

This technique has been applied to the Sc galaxy NGC 6946. The results show that dust extinction significantly affects both the overall brightness and appearance of the galaxy. The total extinction is found to be $A_B = 0.45$ – somewhat larger than the value of $A_B = 0.2$ usually quoted for an Sc galaxy. When corrected for dust the morphology more closely resembles that of an Sb galaxy rather than an Sc galaxy.

The most surprising result of this work is finding interarm regions that suffer high extinction. It appears that these regions appear faint because of the high extinction and not as a result of low stellar density. There are also interarm regions that suffer little extinction; these are therefore truly regions of low stellar density.

Key words: dust, extinction – galaxies: individual: NGC 6946 – galaxies: ISM – galaxies: spiral.

1 INTRODUCTION

The only means astronomers have to study the physics of extragalactic objects is by measuring the electromagnetic radiation they produce. Embedded in this process is the implicit assumption that the energy we measure represents the true output. This may not be the case for studies of disc galaxies at UV and optical wavelengths. Dust contained within their interstellar media will extinguish some of the light, reducing its measured intensity. As the distribution of the dust (and therefore the extinction) within the interstellar medium is likely to be non-uniform, we could also be misled about the observed morphology of disc systems.

In this introduction, previous investigations and methods used to study opacity are discussed. I will argue the case that none were conclusive, providing clear motivation for a more detailed study.

1.1 Surface-brightness/inclination tests

The first attempt to quantify the dust effects in disc galaxies was by Holmberg (1958), who studied the variation of galaxy surface brightness with projected inclination. As a galaxy is tilted to higher inclinations our line of sight intercepts a longer path-length of stars, and the galaxy should therefore appear brighter. If, however, the galaxy contains a large amount of dust, then we would receive light from only one mean free path into it; its surface brightness would therefore be the same at all viewing angles. By analysing the surface brightness (or some related property) of a galaxy when viewed at different angles it should be possible to study the dust extinction. Of course, it is not possible to carry this out on an individual galaxy, but by using the thousands of known galaxies, projected at random inclinations, it should be possible to carry out this test on a statistical basis. Holmberg did this and concluded that galaxies behaved as though they were optically thin; dust effects were small.

A similar analysis carried out by Heidmann, Heidmann & de Vaucouleurs (1972a,b,c) reached similar conclusions. This result was included in the RC2 catalogue (de Vaucouleurs, de Vaucouleurs & Corwin 1976), and it become 'common knowledge' that galaxies were optically thin.

This remained the case until Disney, Davies & Phillipps (1989) showed the interpretation of how galaxies behave in these tests to be ambiguous. They concluded that, for realistic geometries, galaxies should always behave as though they are optically thin, regardless of their true opacity.

Contrary to this prediction, a year later Valentijn (1990) found that galaxies behaved as though they were totally optically thick. Since his test was carried out at the $B\mu = 26$ mag arcsec^2 isophote, he concluded that galaxies were optically thick out to this radius. For this to happen, there would need to be an another component of dust with a scaleheight perpendicular to the plane larger than that of the stars, *in addition* to the dust component which produces the distinctive dust lanes seen in edge-on galaxies. The implication of this result is that optical observations of galaxies barely scratch the surface, and our understanding of galaxies may need to be revised. Burstein, Haynes & Faber (1991) and Choloniewski (1991) postulated the existence of surface-brightness selection effects in Valentijn's sample. These were later shown to exist by Davies et al. (1993). Burstein et al. (1991) and Choloniewski (1991) removed the selection biases present in Valentijn's test by requiring that distances be known to all galaxies in the sample. Despite this, they also found that galaxies behaved as though they were optically thick, adding further weight to the suggestion that our understanding of extinction in disc galaxies needed reviewing.

The results of Burstein et al. (1991) and Choloniewski (1991) were shown to suffer from a new selection effect by Davies, Jones & Trewhella (1995). The telescopes used to obtain the redshifts had a maximum range of 12 000 km s^{-1}, which is not large enough to contain a representative sample for this test. Davies et al. (1995) showed that the Burstein et al. (1991) test always predicts high opacity for a redshift cut-off of 12 000 km s^{-1}, regardless of the true opacity. The cut-off would need to be extended to 24 000 km s^{-1} for the test to work. At this point in time, it seemed that not only could we not relate how galaxies behave in a surface-brightness/inclination test to their opacity, but we could not even measure how they behave.

Recently, Jones, Davies & Trewhella (1996) showed that the selection effects can be modelled and actually used to investigate the opacity. The UGC, ESO and RC2 catalogues all seem to behave as though they are optically thin, as predicted if the standard geometry applies (Disney et al. 1989). Of course, this still does not mean that they are actually optical thin, but knowing how they behave gives hope that we may be able to correct measured galaxy diameters and magnitudes to some universal scale for comparison (e.g., face-on), even if they scale is not dust-free.

1.2 Energy balance

When optical energy is absorbed by dust, it is not destroyed; it will heat the dust, which will then reradiate the energy at far-infrared wavelengths. If we compare the optical to the far-infrared energy output of a galaxy, we should be able to study its opacity.

Jura (1980) argued that the constancy of galaxy surface brightness (Freeman 1970) could be caused by dust in their interstellar media. Jura (1982) predicted that if galaxies were optically thick, then the forthcomong *IRAS* mission should be able to detect them with ease.

However, when the *IRAS* mission flew and unexpectedly detected thousands of galaxies with high far-infrared outputs, the cause was not attributed to opacity but to star formation. After all, galaxies were known to be optically thin. Whether the far-infrared emission is due to star formation or general disc opacity is, at some level, semantics. Everyone agrees that the observed far-infrared energy is due to starlight that has been absorbed and reradiated by dust. The problem is that stars are formed in compact regions of high opacity that may dominate the infrared emission but contribute little to the overall disc opacity. The debate between star formation and disc opacity as the source of the far-infrared radiation is thus equivalent to determining the level of clumpiness present in the emission. The poor resolution of the *IRAS* satellite (~ 1 arcmin) cannot distinguish between the two scenarios.

The most common way used to separate the dust heating due to the general disc extinction from that in star-forming regions is to examine the spectrum (typically four *IRAS* points at 12, 25, 60 and 100 μm). The simplest deconvolutions have two components. Each component has two free parameters, temperature and normalization (mass). The uncertain long-wavelength emissivity index (β) adds another degree of freedom, and already the problem becomes over-parametrized. Not surprisingly, the large number of authors that have attempted this deconvolution using different initial assumptions and models have reached a wide range of conclusions about the dominant source of the far-infrared emission (Rowan-Robinson 1992; Devereux & Young 1993; Evans 1995; Xu & Helou 1996), leading to large uncertainties in the opacity debate. Another cause of uncertainty is the lack of observations beyond 100 μm; the peak dust emission is expected to occur at wavelengths of 100–300 μm, and the *IRAS* satellite may therefore have missed a large fraction of the energy output. Far-infrared imaging cannot resolve these uncertainties until data with better angular and/or spectral resolution are available.

1.3 Optical/near-infrared imaging

A common technique for measuring the extinction to stars in our Galaxy is to use the colour excess. For example, the $(B-V)$ colour excess is given by

$$\underbrace{E(B-V)}_{\text{excess}} = \underbrace{(B-V)}_{\substack{\text{observed}\\ \text{colour}}} - \underbrace{(B-V)_0}_{\substack{\text{intrinsic}\\ \text{colour}}} \tag{1}$$

$$= A_B - A_V,$$

where A_B is the B-band extinction in magnitudes, and A_V is the V-band extinction in magnitudes. For a screen model (applicable to stars in our Galaxy) the ratio of extinction at different wavelengths is fixed for given dust properties (the extinction law). If a star's spectral type (and therefore its intrinsic colour) is known, the extinction towards it can be simply determined. This technique cannot be simply applied to a whole galaxy, because the relative extinction at different wavelengths is sensitive to the unknown relative geometry of stars and dust, and is not constant for different optical depths.

Block et al. (1994) argued, however, that by using near-infrared observations it is possible to extend the technique to galaxies. They argued that because the optical depth in the K band is 10 times smaller than in the B band, the extinction in the K band (A_K) can be neglected. Equation (1) then becomes

$$\begin{aligned} E(B-K) &= (B-K)-(B-K)_0 \\ &= A_B - A_K \\ &= A_B. \end{aligned} \tag{2}$$

Block et al. (1994) argued that this technique was powerful, because it did not depend on uncertain geometry or clumpiness; it did not require observations at wavelengths longer than 100 μm; the observations were simple to carry out and could be done on the ground; also, the resulting map of extinction has a resolution of ~ 1 arcsec, compared to >1 arcmin from other techniques.

There are two main problems with this technique.

(i) $A_K \neq 0$. For a screen model with a Galactic extinction law $A_B/A_K = 10$, but for other geometries it depends on the optical depth. Some simple trials with more realistic geometries give $1 < A_B/A_K < 10$.

(ii) $(B-K)_0$ is unknown, and there is no 'spectral type' with well-defined colours for galaxies. Not only is the intrinsic colour unknown, it cannot be measured directly because of the extinction. It is also likely that the intrinsic colour of the underlying stellar distribution will vary with position in the galaxy, e.g., the bulge is unlikely to have the same colour as the disc.

2 NEW METHOD

The method proposed here is actually a combination of the colour map and an improved energy-balance method. It is possible to combine them in a way that keeps the good points of both – the good overall normalization of the energy balance, and the spatial resolution of the colour maps.

Our updated energy balance (see below) gives the total extinction in a cell comparable in size to the far-infrared beam. This low-resolution measurement of extinction is then used to define a calibration constant (equation 3) that is applied to every colour map pixel that falls within the cell to give the extinction of that pixel (equation 4).

Re-arranging to combine the two unknowns in equation (2) gives

$$A_B(\mathrm{cell}) - (B-K)(\mathrm{cell}) = \underbrace{A_K(\mathrm{cell}) - (B-K)_0(\mathrm{cell})}_{C_{\mathrm{cell}}} \tag{3}$$

The extinction per pixel is then given by

$$A_B = (B-K) + C_{\mathrm{cell}}, \tag{4}$$

where C_{cell} is the calibration constant of the cell that the pixel falls in. The net result is an extinction map that has both high resolution and absolute normalization.

2.1 Improved energy balance

An energy balance is performed on each cell independently. The energy balance used here makes the following improvements on those performed previously (see Section 1.2).

(i) The *total* extinction from all sources is required to calibrate the colour map. It is not therefore necessary (and, in fact, would be wrong) to separate star formation from general interstellar extinction as sources of dust heating.

(ii) *Infrared Space Observatory (ISO)*[1] (Kessler et al. 1996) observations at 200 μm are used to constrain the spectral energy distribution (SED) beyond 100 μm. The total far-infrared energy is obtained by fitting two 'modified black-body' components to five infrared spectral points (12, 25, 60, 100 and 200 μm).

(iii) Far-infrared contributions are considered from the full range of wavelengths that stars emit over. Often in the past, only the B band has been considered (Saunders et al. 1990). The optical spectral energy distribution is determined by fitting two black-body components to several (at least five) broad-band flux measurements. This 'spectrum' is then split up into 10 'bands' covering the range from 0.1 to 2.5 μm. An initial guess is made at the B-band optical depth, and the optical depths in all the other bands are predicted using the Galactic extinction law (Bianchi, Ferrara & Giovanardi 1996). The amount of light lost (and hence redistributed into the far-infrared) from each band is calculated using a radiative-transfer model that assumes that the dust and stars are distributed exponentially above the disc but does not include the effects of scattering. The far-infrared energy predicted for each band is summed, and the total compared to the observed total; the trial B-band optical depth is then modified. This is repeated until the prediction matches the observations.

The most likely estimates of the extinction and optical depth are produced using the best-fitting spectra (optical and far-infrared) and the standard dust/star geometry ($\zeta = \beta_{\mathrm{d}}/\beta_{\mathrm{s}} = 0.5$). Rather than attempting to derive some error limit on these numbers, it was decided to determine the maximum and minimum values that could conceivably be consistent with the data. The maximum extinction is obtained by combining the lowest total flux optical fit with the highest total flux far-infrared fit and using a high value of the layering parameter ($\zeta = 0.7$). The minimum extinction is obtained by combining the highest total flux optical fit with the lowest total flux far-infrared fit and using a low value of the layering parameter ($\zeta = 0.3$). The maximum optical depth is obtained by using the lowest total flux optical fit with the highest total flux far-infrared and a low value of the layering parameter ($\zeta = 0.3$). The lowest value of the optical depth is obtained using the highest optical flux fit with the lowest far-infrared flux fit and a high value of the layering parameter ($\zeta = 0.7$).

3 DATA

3.1 Observations

Optical maps in the B, V, R and I bands were obtained in 1996 April with the 0.9-m telescope at Kitt Peak using the t2ka CCD camera, which has 2048×2048 pixels of 0.68 arcsec each, giving a field of view of 23.2 arcmin. The total exposure times were 20 min in the B, V and R bands, and 10 min in the I band. The images were reduced using Starlink

[1] Based on observations with *ISO*, an ESA project with instruments funded by ESA 'Member States' (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) with the participation of ISAS and NASA.

software, and calibrated using the aperture photometry of Engargiola (1991).

A near-infrared map in the *K* band was obtained in 1995 November with the 2.5-m Wyoming Infrared Observatory using MIRC, which has 128 × 128 pixels of 2.23 arcsec each, giving a field of view of 4.7 arcmin. The final picture is made up of a 2 × 2 mosaic with an integration time per position of 24 min. The images were reduced using Starlink software, and calibrated using the aperture photometry of Aaronson (1977).

Calibrated *IRAS* HiRes far-infrared maps at 12, 25, 60 and 100 μm were obtained from IPAC. These have a resolution of 60–100 arcsec (FWHM), are sampled on to a 15-arcsec grid, and cover a 1° × 1° area.

A far-infrared map at 200 μm was obtained in 1996 December using the C200 detector of the ISOPHOT instrument (Lemke et al. 1996) aboard *ISO*. The maps were made using the over-sampling mapping mode (AOT P32); the sampling along the in-scan and cross-scan directions was 31 and 93 arcsec respectively. Reduction of the data was carried out using the ISOPHOT interactive analysis software package (PIA v6.0),[2] allowing correction for non-linearity in the detectors and deglitching. The signal was converted to MJ sr^{-1} using the internal fine calibration source, which was observed before and after the galaxy to monitor detector responsivity drifts. The final map has 31-arcsec pixels and a resolution of 117 arcsec (FWHM). The map covers an area of $\sim 22 \times 18$ $arcmin^2$.

3.2 Additional processing

The local background (sky in the optical and near-infrared, and cirrus in the far-infrared) was subtracted from each image. The contribution to the overall flux from local stars was eliminated by masking the stars by eye. The galaxy flux in the masked regions was estimated using a 2D linear interpolation of the flux in the surrounding area. This treatment was required for many stars in the optical and near-infrared, but only one star was visible in the far-infrared.

All the data were smoothed to the worst resolution of 117 arcsec, *ISO* at 200 μm (Tuffs et al. 1996). In the optical and near-infrared, this was achieved by smoothing with a Gaussian of 117 arcsec. For the *IRAS* images, an initial guess was made at the required smoothing Gaussian by assuming that the FWHMs of the Gaussians add together in quadrature. This initial guess was used to smooth the *IRAS* beam maps in the vicinity of NGC 6946 (a standard product with HiRes data), and the resulting beamsize and shape were measured. The initial guess was adjusted until the beam became circular with a FWHM of 117 arcsec.

Finally, the *ISO* 200 μm data was binned up by a factor of 4 in each direction, giving a map with 124-arcsec pixels (cells). These were chosen to be just larger than the beamsize to ensure that each cell was an independent sample. The smoothed maps at all the other wavelengths were transformed and resampled on to the same grid using the central peak in flux as a reference point, and converted into units of Janskys (per cell). The 200-μm and *B*-band cell maps are shown in Fig. 1 as an example.

A FORTRAN program was then written to read in the flux values from each of these 10 maps, fit the spectrum, and calculate the extinction and optical for each cell. The outputs were written into six images of the best, highest and lowest optical depth and extinction.

To make the $(B-K)$ colour maps, the *B*-band image was transformed and resampled to have the same size, orientation and pixel scale as the lower resolution *K*-band image. The *K*-band image was divided by the *B*-band image, and the resulting map converted to a magnitude scale.

4 NGC 6946

NGC 6946 is an Sc galaxy viewed at an inclination of $i = 31°$, and it lies at a distance of 5.5 Mpc (Tully 1988). At this distance an angle of 1 arcsec corresponds to a physical size of ~ 25 pc. NGC 6946 is thought to have active star formation throughout its disc, and a mild starburst at its centre (Tacconi & Young 1990). Its spiral arm structure has been classified as type 9 by Elmegreen & Elmegreen (1984); in

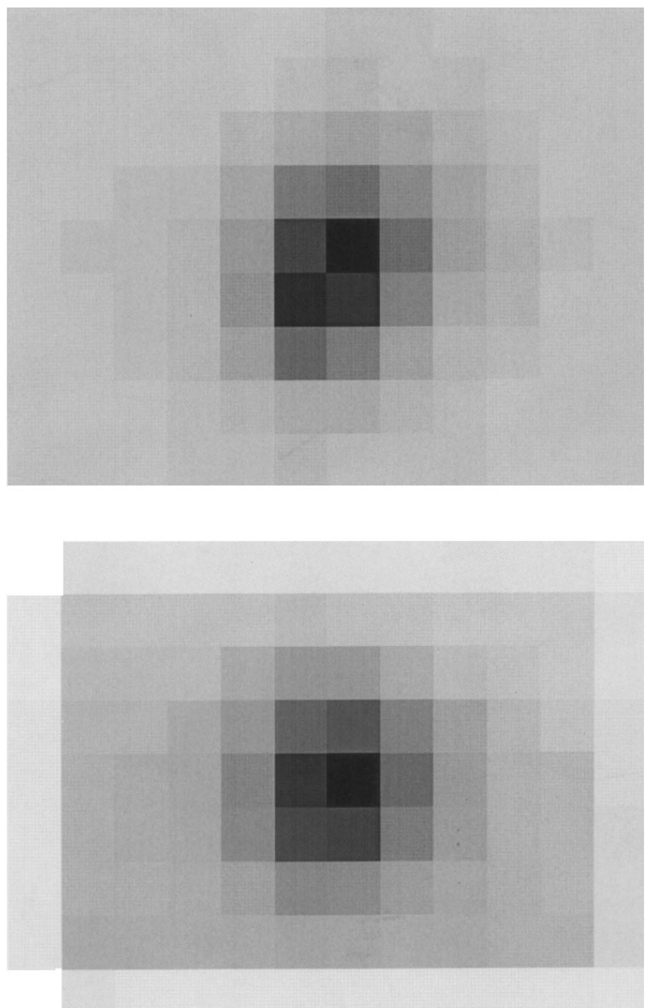

Figure 1. The *B*-band image (top) and the 200-μm image (bottom) after processing into cell maps.

[2] PIA is a joint development by the ESA Astrophysics Division and the ISOPHOT Consortium led by the Max Planck Institute for Astronomy (MPIA), Heidelberg. Contributing ISOPHOT Consortium institutes are DIAS, RAL, AIP, MPIK and MPIA.

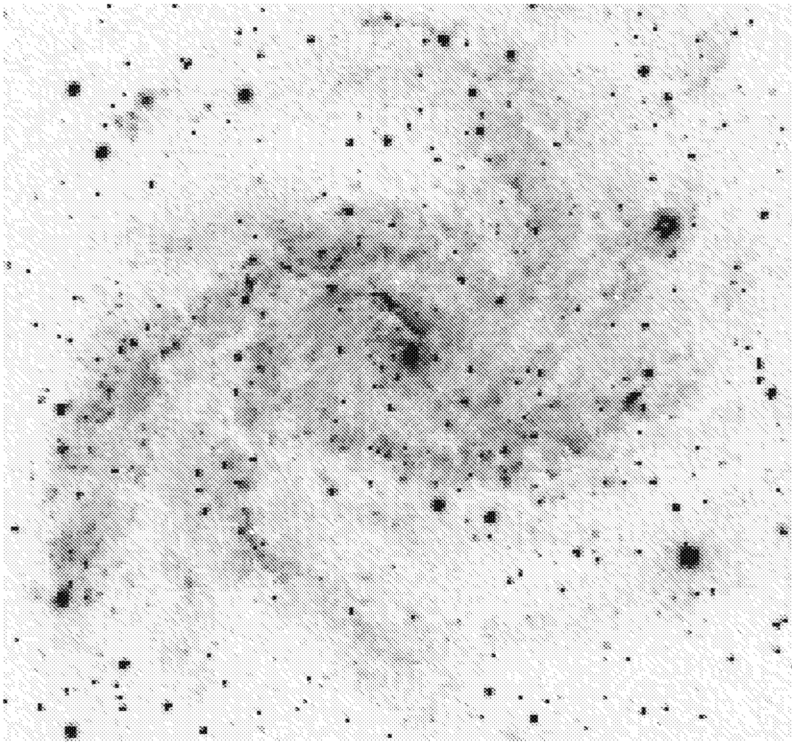

Figure 2. *B*-band image of NGC 6946. North is to the top left, and east to the bottom left. The pixel scale is 2.23 arcsec, corresponding to 60 pc in the galaxy.

this classification scheme, type 6 corresponds to flocculent arms, and type 12 to a classic grand-design spiral structure. Tacconi & Young identify six spiral arms emanating from the centre. The most striking of these is the strongly developed, luminous arm in the north-east, in contrast with poorly defined spiral structure in the south-west. The *B*-band image (transformed to the same size, orientation and pixel scale of the *K*-band image) is shown in Fig. 2.

4.1 Energy-balance results

The optical depth and extinction maps are shown in Fig. 3. The optical depth is shown on the left, and the extinction on the right. The top maps show the most likely values, the middle maps show the lowest possible values, and the bottom maps show the highest possible values. The extinction and optical depth represented by each grey level is shown by the key at the top of each column. Each cell corresponds to a physical size of ~ 3 kpc. It can be seen that the extinction at the centre is high ($A_B = 0.8$ means that only 45 per cent of the *B*-band light escapes), and that it drops off towards the outer regions of the galaxy (> 75 per cent escapes there). The total extinction of the whole galaxy is $A_B = 0.45$, considerably higher than the $A_B = 0.2$ prescribed for an Sc galaxy in the RC2.

The extinction maps are constrained reasonably well, considering the large variation of estimates between previous studies (see introduction); there is only a 0.3-mag difference between the maximum and minimum and the best-fitting values.[3]

The maps of the absorption optical depth are less well constrained, but show that at least the central regions of NGC 6946 are likely to be optically thick, even in the minimum map. The current observations and understanding of geometry cannot completely rule out the possibility that NGC 6946 is optically thick over the entire face of its disc, as suggested by Valentijn (1990, 1994).

The maps in Fig. 3 show the absorption optical depth; the total optical depth (including scattering) is likely to be double this (see Section 5.1). These results therefore seem to suggest extremely high optical depths. If the dust is patchy, however, these values represent the *average* optical depth. This average could well be made up of small regions of high optical depth, with largely transparent regions in between. The high optical depths need not necessarily imply such a large effective opaque cross-section to background objects.

4.2 Extinction map

The high-resolution extinction map is shown in Fig. 4. The extinction is shown in magnitudes (A_B), with the grey-scale indicated. The first thing to note about the extinction map is the absolute scaling between cells. In the central regions the scaling matches exactly, although in the outer regions where the data becomes noisy the match is not so good. The energy balance was carried out completely independently on each cell; there were no constraints placed on any of the spec-

[3] The maximum and minimum values are derived by combining the most extreme fits in the most extreme ways. It is very unlikely that the errors could conspire to combine in this manner, and the full range of possible values thus represents a much larger range than the true uncertainty.

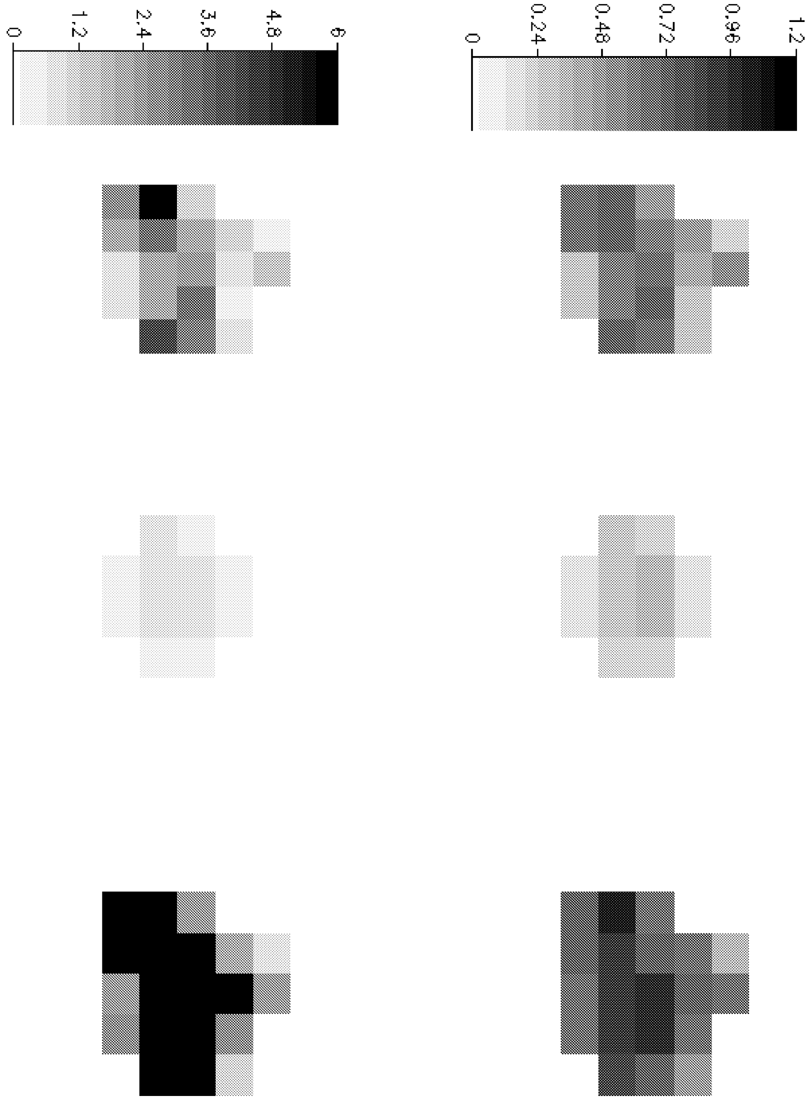

Figure 3. Maps of the extinction and optical depth in 124×124 arcsec^2 cells of NGC 6946. The optical depth is shown on the left, the extinction on the right, with the grey-scale key at the top of each column. The top maps show the best-fitting results, the middle maps show the lowest results that could be consistent with the data, and the bottom maps show the highest results that could be consistent with the data.

trum fitting or the optical depth and extinction calculations. To find that the independent energy balance results from individual cells are consistent would be reassuring, and to find as good a match as shown in Fig. 4 provides evidence that the technique is reproducible and fairly accurate.

The extinction map shows that there are two quite distinct causes for an apparent lack of light in a *B*-band image. The *B*-band intensity at a given position can be faint either because it is intrinsically faint or because there is an abnormally high dust extinction present. What appears to be an apparent interarm region between the two prominent north-east arms is shown to be the site of strong extinction. Note also how the dark filamentary structures that wind along and across the arms in the *B*-band image are picked out as high-extinction regions. In contrast, the interarm region in the north-west shows almost no extinction. This is therefore a true interarm region with a low stellar density.

One interesting feature to note on the extinction map is the very high extinction at the centre. In the central regions less than 4 per cent of the *B*-band light escapes the galaxy. The central peak in extinction does not correspond exactly to the centre of the galaxy; it is actually located approximately 6 pixels ($\sim$ 300 pc) south-west of the optical centre. As heavy dust extinction is associated with active star formation, it is likely that this is the site of the nuclear starburst. Strong evidence that the feature is real and due to dust is provided by high-resolution aperture synthesis CO observations of NGC 6946 (Ishizuki et al. 1990). Ishizuki et al. find a small, barely resolved, feature in the observations, which they interpret as a disc of molecular material at the centre of NGC 6946. Examination of their contour map shows that this disc of material is offset from the centre, and corresponds well in size and shape to the extinction feature. The resolution of the extinction map, however, is at least two times better, showing the power of this technique to achieve high resolution.

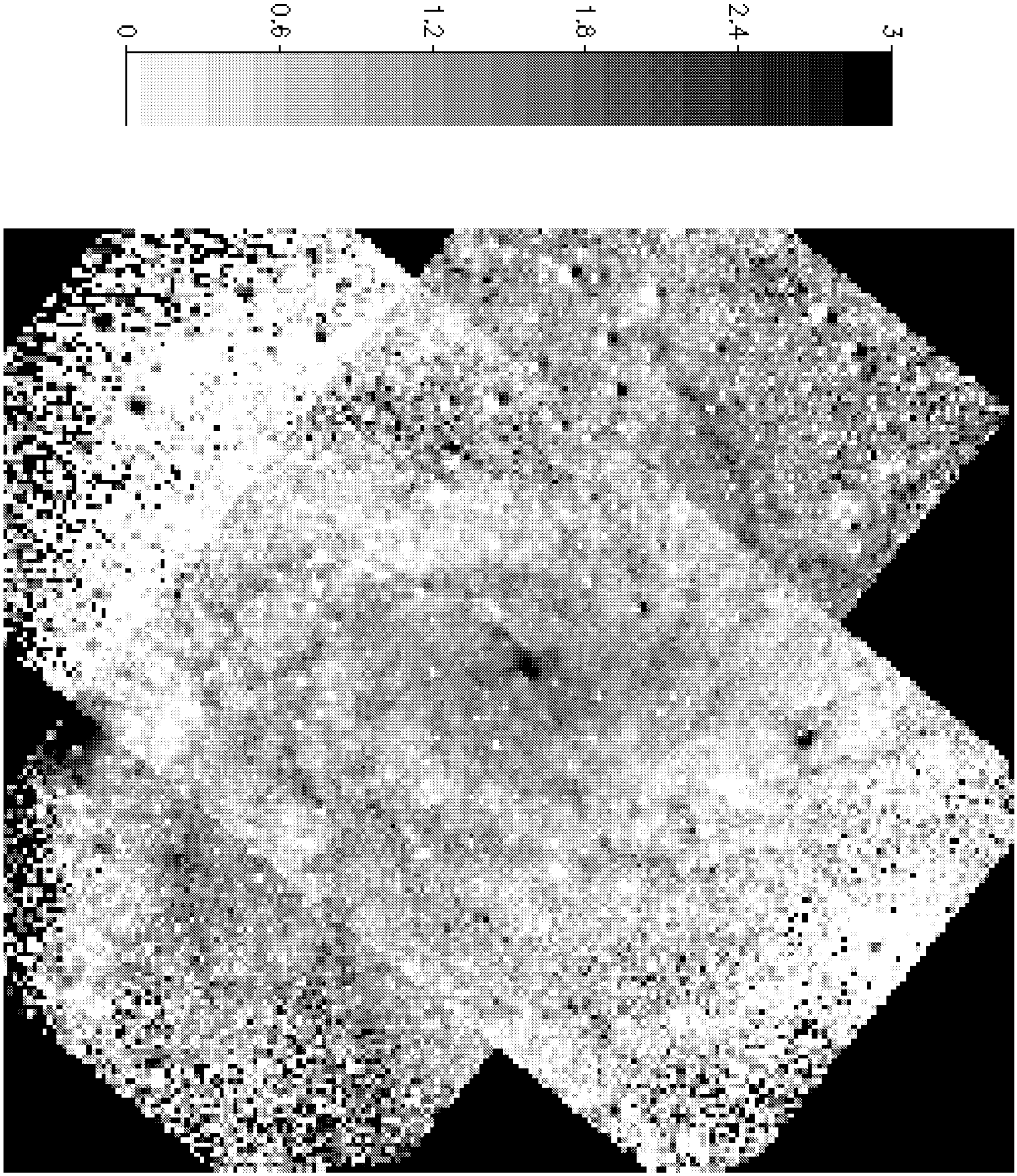

Figure 4. Extinction map of NGC 6946. The *B*-band extinction (A_B) is shown in magnitudes indicated by the grey-scale.

4.3 Dust-free map

If the amount of light lost due to dust at every position in a galaxy is known, it is possible to add this extinguished light to the original image to obtain a picture of the galaxy as it would be seen without dust. This 'dust-free' map of NGC 6946 is shown in Fig. 5, with the same size, orientation and linear intensity scale as the observed image (Fig. 2). The most obvious thing to note is the relative brightness of the images; the reconstructed image is considerably brighter than the observed image. This demonstrates how effective dust can be at extinguishing starlight. The other clear differ-

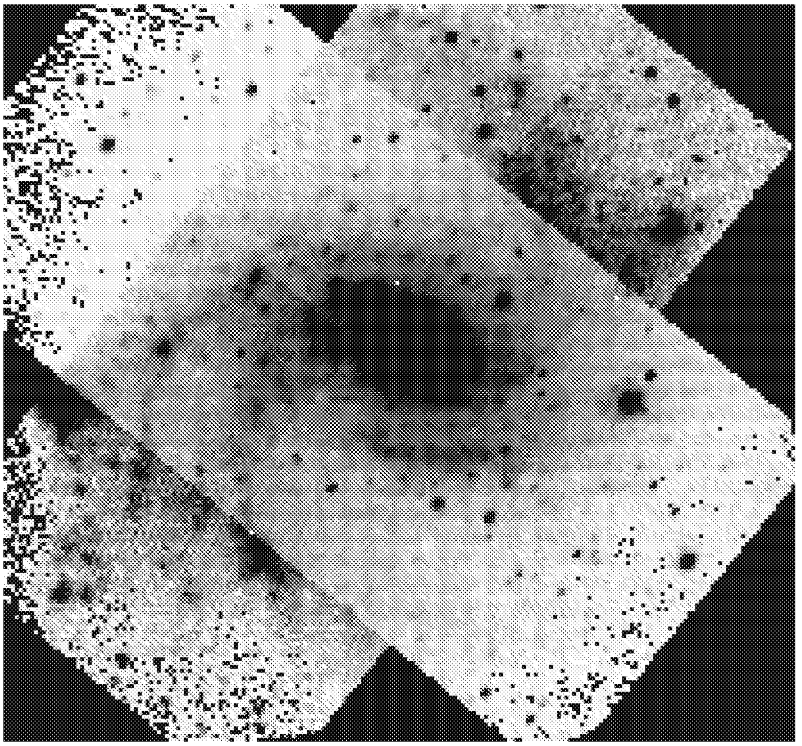

Figure 5. Reconstructed 'dust-free' *B*-band image of NGC 6946. The image is shown at the same size, orientation and linear intensity scale as the observed *B*-band image in Fig. 2.

ence between the images is the morphology. The bulge is much more prominent in the reconstructed image. If NGC 6946 had been viewed without dust, it would likely have been classified as an Sb galaxy *not* an Sc!

5 DISCUSSION

In the introduction some unanswered questions were posed; these will now be discussed and reviewed in the light of the results of this investigation.

Extinction

It was shown that the extinction of optical light due to dust in the interstellar media of disc galaxies can be mapped with high resolution. The extinction in NGC 6946 was shown to be very patchy, and to be somewhat influenced by the spiral structure in the galaxy. It is not clear whether these changes in extinction are caused by changes in the dust mass or dust/star geometry. Stirring the dust up so that it lies in front of the emitting material may be a far more effective way of producing high extinction than increasing the amount of dust present.

It was shown that extinction can have a dramatic effect on the observed morphology of a galaxy. NGC 6946 appears more like an Sb galaxy rather than an Sc when the extinction is corrected for. The implications in terms of galaxy classification are not yet clear. Do Sb galaxies look like Sa galaxies when corrected for extinction, or are Sc galaxies just dusty Sb galaxies?

Optical depth

Although it has been a focus of attention in this field for some time, the optical thickness of disc galaxies is, in some ways, a less important quantity than the extinction. Much of the concentration of effort on determining the optical depth may well have resulted from the historical notion that extinction and optical depth were essentially equivalent (Trewhella et al. 1997); this is true only where the screen geometry applies (Disney et al. 1989). This geometry does not apply to the internal extinction of discs, but it does apply to the obscuration that a galaxy will present to a background source. It was shown in Trewhella et al. (1995) that if galaxy optical depths were as high in the outer regions as claimed by Valentijn (1990, 1994), Burstein et al. (1991) and Choloniewski (1991), a large fraction of the Universe could be hidden beyond a redshift of $z = 3$. If NGC 6946 is taken as a typical galaxy, these results suggest that the Universe is transparent out to a redshift of $z > 6$. Of course, NGC 6946 may not be a typical galaxy, and more galaxies need to be studied to check this.

Dust distribution

Several papers have suggested the existence of a cold component of dust that is invisible to the *IRAS* observations and has scalelengths in the radial and vertical directions larger than those of the stars (Valentijn 1990, 1994; Burstein et al. 1991; Choloniewski 1991; Beckman et al. 1996). The evidence suggesting the existence of this component has been shown to suffer from selection biases (Davies et al. 1995) or be explainable by other means (de Jong 1996). There is, however, some evidence in the *ISO* data on NGC 6946 as well as the *COBE* maps of the Galaxy to suggest that this component does actually exist (Davies et al. 1997; Alton et al. 1998). This cold dust component probably contains 4–10 times the mass of the warmer component, although its energy output and hence extinction does not dominate except in the outer regions.

5.1 Sources of error

5.1.1 Scattering

Scattering does not destroy optical light; it merely changes its direction. For a thin-screen geometry, any change in direction removes light from the beam and is equivalent to having destroyed it. For other geometries, however, this is not the case. For a spherically symmetric geometry, to a first approximation (single scattering) scattering has little net effect – as much light is scattered into any beam as scattered out of it. As the scattering and absorption optical depths are approximately equal in the *B* band, the total optical depth required to produce a given extinction is approximately double the absorption optical depth.

If multiple scattering occurs, each photon must take a longer path in order to exit the galaxy. This results in increased absorption, lowering the required optical depth for a given extinction. Furthermore, the results of Bianchi et al. (1996) show that scattering in disc systems is not isotropic; light is preferentially scattered out of the plane. As a result, using the far-infrared energy output may slightly over-estimate the extinction of face-on galaxies, and under-estimate the extinction of edge-on galaxies. The effect is small, however (<0.2 mag for extreme inclinations). Nevertheless, this small error in extinction may introduce much larger errors in the optical depth.

If the dust is clumpy, the effects of scattering are greatly reduced, each clump behaving like a large absorbing grain.

In summary, the total optical depth can be estimated from the absorption optical depth by multiplying by 2. In addition to this increase, the unmodelled effects of scattering could introduce large errors in the derived optical depth, up to a factor of 2. The calculated extinction is not so susceptible to errors introduced by neglecting scattering; in NGC 6946 the error introduced is likely to be less than 0.1 mag.

5.1.2 Geometry

Running the models with different geometries shows that the measured extinction remains relatively constant (less than 10 per cent change) when the layering parameter (ζ) is varied from 0.1 to 0.9. As with scattering, the optical depth is much more susceptible to changes in the model, increasing the uncertainties in its determination.

If the dust is clumped, it can have one of two effects. If the clumpiness is random with respect to the stars, it will make the extinction 'greyer', i.e., the extinction as a function of wavelength will be more equal. This will have the effect of increasing the contribution of the red and infrared light to the far-infrared. If the clumpiness of the dust is correlated with the clumpiness of the young stars, as may be the case (Xu & Helou 1996), it will increase the contribution of the UV and blue light to the far-infrared.

It is not clear exactly how either situation would affect the *B*-band extinction and, as little is currently known about the way in which dust clumps with stars, it is not included in this study, although future knowledge of this could have bearing on these results.

5.1.3 SED fitting

As the extinction in a disc system varies slowly with wavelength, the strongest factor in deciding how much a particular band contributes to the far-infrared is how much light there is to extinguish. It is therefore important to sample as much of the optical SED as possible to improve the accuracy of the fits. In this work the optical SED is sampled at five points from 0.4 to 2.2 μm. If the energy output shortward of 0.3 μm is significantly larger than the extrapolation of the fits, then the UV extinction will be underestimated. If this is the case, then the extinction in the other bands will be over-estimated to compensate. Observations at shorter wavelengths are required to investigate this possibility.

Although it appears that the peak in dust emission lies somewhere between 100 and 200 μm, there may still be some emission at wavelengths longer than 200 μm, and this should be measured with submillimetre observations.

5.1.4 Resolution

The intrinsic colour of the ensemble of stars in a galaxy at any point is likely to vary with position. The resolution of the calibration constant would ideally be better than the likely distance scale over which the intrinsic colour is likely to vary. The most dramatic colour changes are likely to occur in the spiral arms; thus the resolution should be of order the width of an arm. This goal is not quite achieved in NGC 6946, due to the poor resolution of the C200 detector on *ISO*. It is therefore possible that the high extinction calculated in the north-east interarm region could be the result of very blue stars in the spiral arms. Although this is likely to contribute to the amplitude of the calculated extinction differences at some level, it is unlikely to be the dominant cause of the feature for the following reasons. If the calculated extinction feature were due to colour variations alone, both interarm regions would show up as having high extinction; this is not the case. The interarm region that shows high extinction has a very filamentary structure in the *B*-band image, and shows obvious dust lanes crossing the arms. In contrast, the low-extinction interarm regions appear smooth and relatively dust-free in the optical image.

5.2 Future work

ISO observing time was awarded to map a total of 10 disc galaxies at 200 μm. These galaxies are of mixed morphological type and have different levels of infrared output and starburst activity; this will allow us to examine the importance of these properties on the energy balance and the extinction.

The radiative transfer models will be improved to take into account scattering and clumpiness.

The wavelength coverage of the observations both in NGC 6946 and the other galaxies will be extended to cover the full range from UV to submillimetre. This will be achieved with the addition of ground-based *U*-band CCD imaging, space-based UV imaging from the *ASTRO* missions, full grating spectra from 42 to 197 μm from the LWS instrument on *ISO*, and submillimetre mapping at 350 μm from SHARC at the CSO, and at 450 and 850 μm from SCUBA at the JCMT.

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